Atmospheric, Oceanic, and Space Environment Research at APL

Lawrence J. Zanetti

Environmental research is being pursued in several areas at APL to understand the science of atmospheric and space processes and apply that knowledge to finding technological solutions to problems of interest to our sponsors. Two areas are specifically addressed in this article: (1) atmospheric, oceanic, and littoral environment research as it affects input to radar propagation codes, and (2) space weather research as it impacts the "Geospace."

INTRODUCTION

An interactive approach is a hallmark of the APL culture and the basis of our ability to solve technological problems. Sponsor tasks are accomplished by a diverse staff working on highly integrated teams. The various elements of the Laboratory's approach include

- Good communication among science and engineering staff members throughout the life cycle of a project
- An APL-wide professional interest in formulating and proposing projects to sponsors
- An understanding of basic scientific problems and needs
- Development of mission or system concepts and architectures
- Fabrication and integration of the needed technology
- Implementation of mission goals
- Communicating, publishing, and reporting results—especially as they impact the global population

This approach, which is, by definition, an end-to-end systems approach, is followed to investigate and model the environment in order to understand its scientific processes and its effects on system performance. (The end-to-end systems approach is detailed later in this article.) The central themes developed below fall within two areas of APL expertise that include both basic research and application of the same to technological products: (1) atmospheric and oceanic research as it affects radar propagation, and (2) the space environment as it affects technology.

The analysis here is not meant to be all-inclusive, but rather representative of APL's end-to-end approach. Information contained in the article is based on presentations to the APL Senior Leadership Technology Team. Presenters—who are, in effect, co-authors of this article—and topics addressed are listed in the boxed insert.

SPACE, ENVIRONMENT, AND SYSTEM PERFORMANCE EFFORTS AT APL

Atmospheres, Ocean Research/Radar Propagation
- *Parabolic Equation Propagation Modeling (2D)*
  J. Z. Gehman, R. S. Awadallah, G. D. Dockery, J. R. Kuttler, and M. H. Newkirk
- *Environmental Characterization Methods*
  M. H. Newkirk, D. Dockery, C. Etheridge, J. Goldhirsh, G. Konstanzer, and J. Rowland
- *Atmospheric Input to TEMPER: Prediction of Atmospheric Variability over Complex Terrain*
  C. E. Schemm, L. P. Manzi, C. C. Lin, and R. Rzemien
- *University Partnering for Operational Support: Space/Terrestrial Weather Products*
  D. J. McMorrow, E. E. Hume Jr., A. T. Y. Lui, C.-I. Meng, and G. E. Baer
- *WITS: Wave Identification and Tracking System—Spectral Analysis, Wave Isolation*
  J. L. Hanson and M. Mandelberg
- *3D Radar Propagation Modeling*
  R. S. Awadallah
- *Computational Complexity*
  H. C. Ku
- *Acoustic Waveguides, Internal Wave Scatter*
  A. P. Rosenberg
- *Delay-Doppler Radar Development*
  R. K. Raney and J. R. Jensen
- *Investigation of the Coupling of Unwanted Electromagnetic Signals into a PC*
  D. E. Freund, A. W. Bjerkaas, and I. Kohlberg

Space Environment/Space Weather
- *TIMED*
  E. R. Talaat and J.-H. Yee
- *STEREO*
  A. S. Driesman and D. M. Rust
- *ACE Real-Time Solar Wind*
  D. K. Haggerty, G. C. Ho, D. Lario, S. E. Hawkins III, E. C. Roelof, and R. E. Gold
- *Living With a Star Program*
  L. J. Zanetti, K. A. Potocki, P. D. Bedini, and L. J. Frank
- *NEAR Landing*
  G. A. Heyler and A. G. Santo
- *SHIELD Architecture*
  R. E. Gold
- *SPARCL: High Speed Secure Communications*
  S. S. Badesha, A. D. Goldfinger, P. F. Bythrow, and J. C. Bunn
- *Space Advanced Technology Development*
  B. E. Tossman and R. E. Gold
- *Formation Flying: Distributed Platforms*
  P. A. Stadter, A. A. Chacos, R. J. Heins, G. T. Moore, T. L. Kusterer, M. S. Asher, G. A. Marcus, and W. S. Devereux
- *Realistic Interstellar Explorer*
  R. L. McNutt

ATMOSPHERE, OCEAN RESEARCH/RADAR PROPAGATION

Radar Performance Models

APL has a long history of innovative radar and missile defense systems work including development of the Aegis AN/SPY-1 radar system and the Harpoon, Standard Missile, and Tomahawk weapons systems in support of the Fleet. In the early 1980s, field tests of the AN/SPY-1 radar revealed the need to more accurately account for and ultimately model atmospheric effects on radar propagation. APL's Submarine Technology Department (now the National Security Technology Department [NSTD]) responded by developing the Electromagnetic Parabolic Equation (EMPE), leveraging work done by Hardin and Tappert[1] in the 1970s for underwater acoustic propagation. Over the last two decades, APL has been at the forefront of parabolic equation (PE)–based propagation modeling, and numerous Navy design studies and field tests have benefited. The culmination of these efforts, the Air Defense Systems Department's (ADSD) Tropospheric Electromagnetic Parabolic Equation Routine (TEMPER) model, is widely regarded as the Navy's benchmark PE model and is currently used by nearly 30 organizations. Table 1 gives a time and event history of the development of the TEMPER model.

TEMPER uses an approximation to the vector wave equation that has two important qualities: (1) it affords numerically efficient solutions, particularly by employing Fourier methods, and (2) it is well suited for modeling electromagnetic propagation in the lower atmosphere. With this efficient and accurate approach, radar system engineers can model the way atmospheric conditions enhance or reduce radar coverage and signal return. This capability is vital because the troposphere can drastically alter radar performance.

Figure 1 displays different idealized atmospheric conditions and their effect on propagation strengths. The first set on the left shows the "standard" atmospheric model of refractivity within the troposphere as a function of altitude, and the corresponding radar propagation strength as a function of altitude and range. The other three sets show "nonstandard" refractivity profiles, paired with the corresponding TEMPER range/height coverage plots. Subrefraction is a condition where the atmosphere bends radar waves upward, severely reducing radar coverage. At other times, the

Table 1. Development of the TEMPER radar propagation code.

Year(s)	Event
1973	Efficient Fourier methods first applied to the PE in numerical routines
1979	Aegis Shipbuilding Program Office (PMS-400) begins funding APL's SPY-1 modeling and simulation
1979–1982	Aegis SPY-1 field tests reveal need for an accurate propagation model
1984	EMPE successfully used for Terrier post-test analysis
1987	EMPE licensed and sold commercially
1988	Improvement on EMPE culminates in TEMPER
1989	TEMPER accurately models imperfectly conducting surfaces
1996	More rigorous terrain method (linear shift map) added to TEMPER
1998	TEMPER 3.0 made available to nearly 100 users in more than 20 organizations
Fall 2000	TEMPER 3.1's reformulated discrete mixed Fourier transform improves numerical stability

atmosphere contains layers, called ducts, where radar waves bend downward so severely that they become trapped in the layer. Ducts have profound effects on radar coverage and also cause false returns from ground reflections. Being able to model these effects accurately has given the United States a distinct advantage in the performance of radar defense systems and missile technology. Future designs will benefit from next-generation propagation and atmospheric models that are being prototyped by the Research and Technology Development Center,

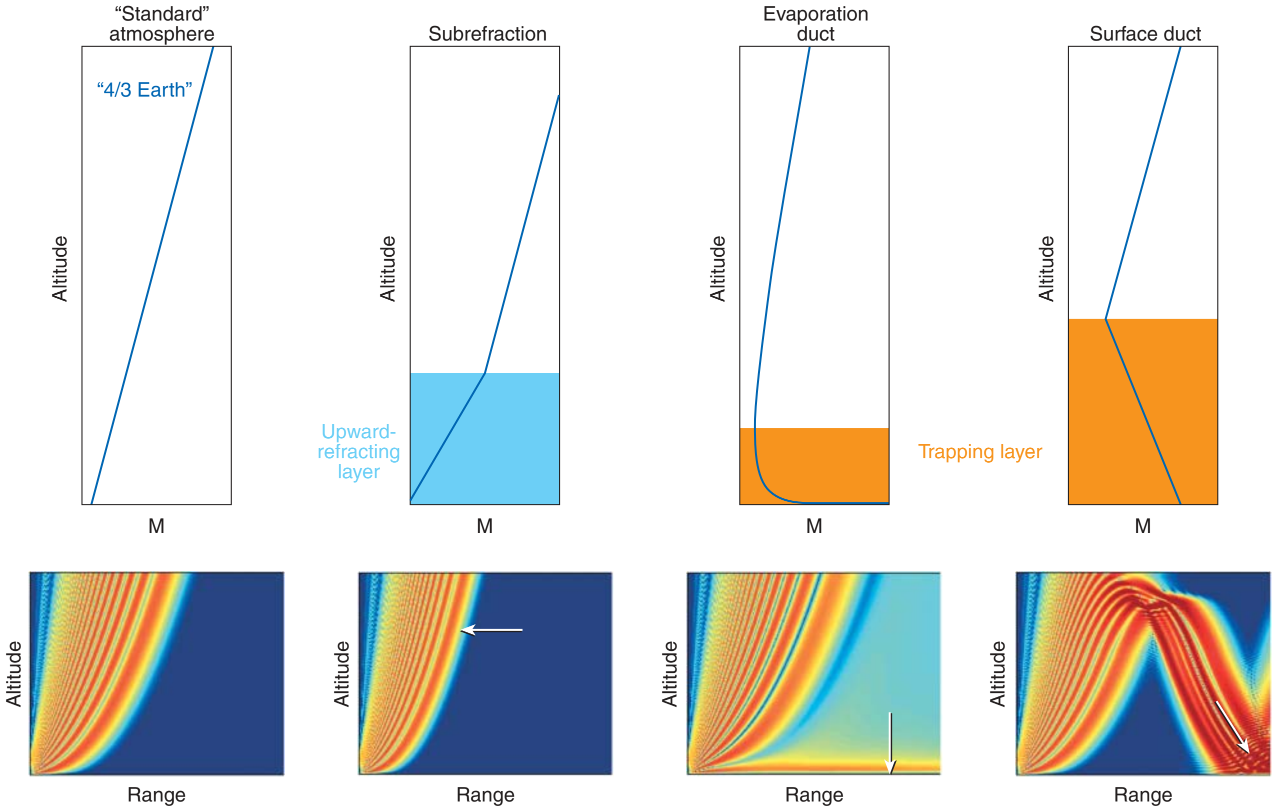

Figure 1. Prior to TEMPER, a "standard" atmosphere was often assumed in radar analysis. However, refractivity in the lower atmosphere can deviate significantly from the standard model. This figure compares propagation in a standard atmosphere to three nonstandard atmospheric conditions. Upper row shows refractivity as a function of altitude (M = modified refractivity). Bottom row shows corresponding radar coverage as a function of altitude and range (red = strongest illumination); arrows point out significant deviations from standard coverage.

ADSD, and NSTD. A more thorough discussion of past, current, and future efforts can be found in Ref. 2.

Intrinsic to these propagation code developments has been proper environmental understanding. One means of improving radar propagation modeling is the introduction of more sophisticated atmospheric models such as the Regional Atmospheric Modeling System (RAMS) developed by Colorado State University. RAMS is a simulation model of atmospheric dynamics based on state-of-the-art atmospheric research. RAMS uses the principal components of the end-to-end model to predict radar propagation and clutter in coastal and mixed-terrain environments, where spatial and temporal variations in meteorological variables in the range direction are known to be important. Atmospheric data, either from shipboard measurements or global/regional analyses, are input to RAMS. RAMS provides predictions of the three-dimensional fields of temperature and humidity, which in turn are used to calculate radar refractivity over a typical 12- to 24-h forecast period. Estimates of refractivity for selected transects are used along with the appropriate radar parameters as inputs to TEMPER. TEMPER output is then input to the radar scattering (RADSCAT) model, which predicts clutter.

Figure 2 shows results from a sample 24-h prediction using RAMS. The model was initialized with a single vertical profile of temperature and humidity obtained from a radiosonde launched from USS *Lake Erie* (CG 70) in the Arabian Gulf at 2100 UTC on 7 October 1999. Figure 2a depicts predictions of modified refractivity along a horizontal profile starting at the location of the *Lake Erie* and extending over land into Saudi Arabia. Figure 2b shows corresponding TEMPER predictions of radar propagation loss along the same path. The early morning (0230 UTC) results show evidence of a surface duct that is clearly not present later in the day (at 1600 UTC) and has a demonstrable effect on radar coverage. Figure 3 shows a horizontal map of coastal

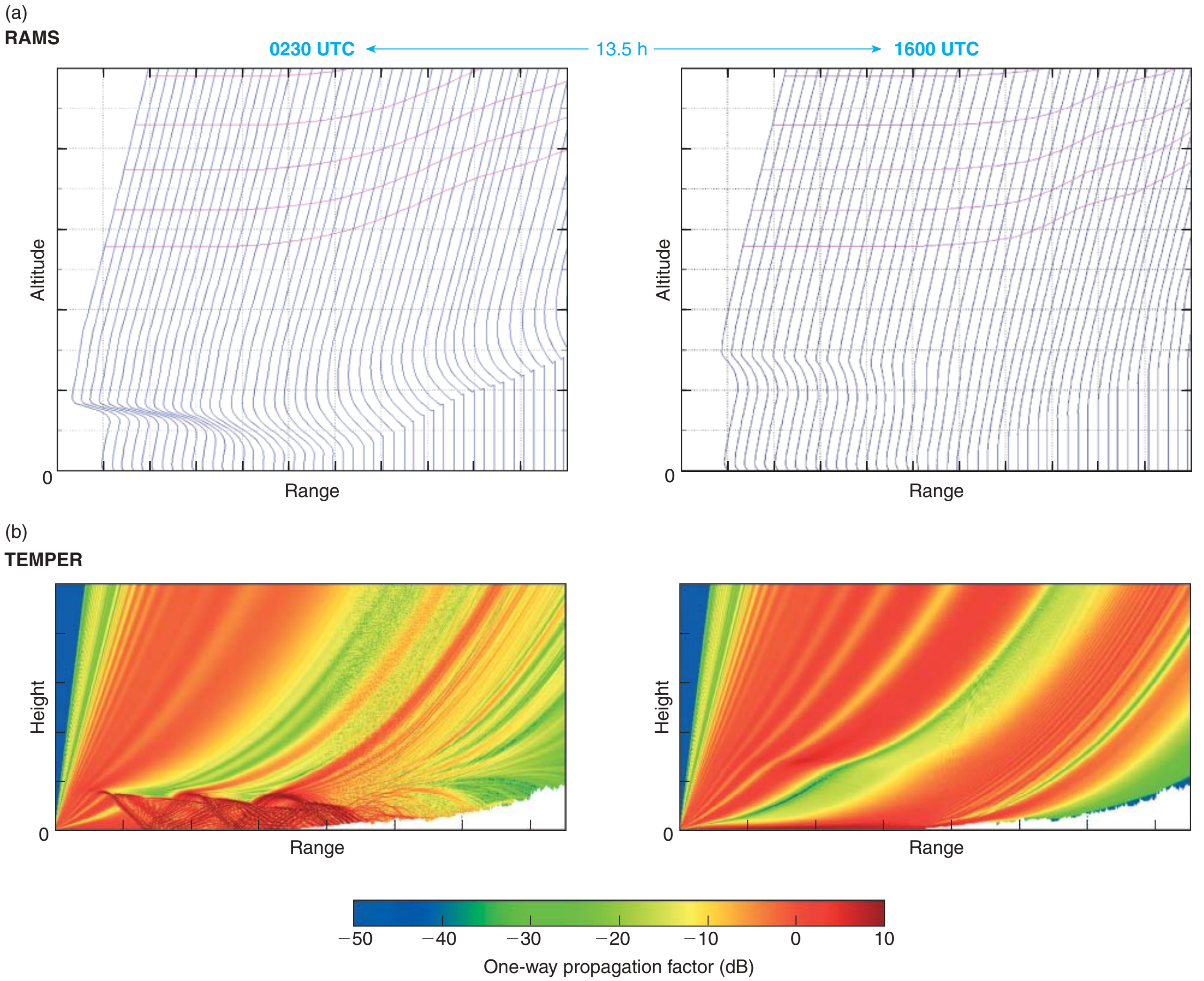

Figure 2. Vertical profiles along a 240° transect comparing (a) measurements in a coastal environment (including RAMS) versus (b) TEMPER predictions of propagation refraction. Note the significant profile changes in 13.5 h.

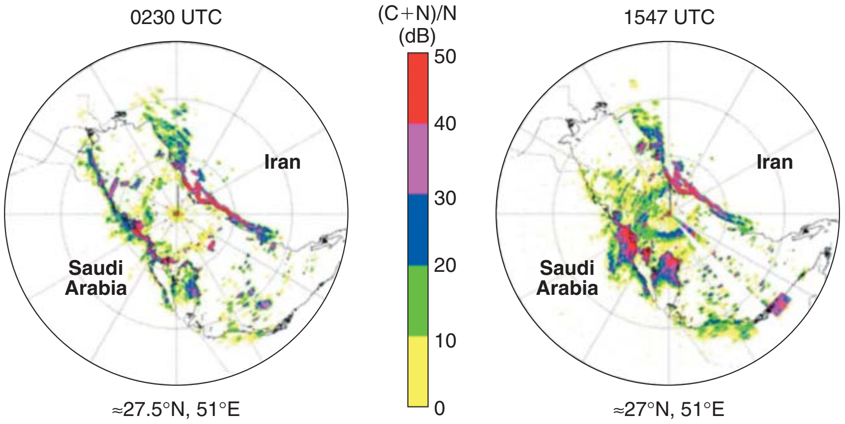

Figure 3. Horizontal maps of clutter observed during the same time periods covered in Fig. 2. Measurements verify predicted radar clutter at coastal interfaces as well as significant changes over many hours.

clutter measurements that verify the regional change in atmospheric conditions within the same time frame.

APL's participation in the University Partnering for Operational Support (UPOS) program is another means by which the Laboratory is involved in fundamental research to improve radar performance. UPOS is an initiative to adapt state-of-the-art university research results to the operational support requirements of the Army and Air Force. The need for UPOS is based on DoD's constant search for ways to improve and update support to the warfighter and strategic customers while reducing costs. It is because of the general civilian and military requirement to reduce costs that universities are coming under increasing pressure to show the relevance of sponsored research.

UPOS has delivered a number of prototype operational products in atmospheric and space science to the Air Force Weather Agency. Figure 4 depicts one such product that translates traditional vertical range radar profiles into horizontal Web-based, two-dimensional maps with geographical locators. These maps address the need of radar operators to produce horizontal fans depicting radar propagation performance. This is accomplished by using high-resolution terrain and gridded weather with three-dimensional variability over the theater.

Finally, as noted earlier, radar propagation modeling requires atmospheric research and the ability to compensate for the effects of the land/sea (littoral) interface. However, it is unusually difficult to analyze atmospheric effects near coastlines and continental ice sheets with satellite radar altimeters used today, which have limited observation capabilities. To improve upon measurements taken by these satellites, APL is developing a delay/Doppler radar altimeter that takes advantage of coherent signal processing strategies to achieve a more efficient and accurate means of measuring wave height at land/sea interfaces from space (Fig. 5). The Laboratory is funded under NASA's Instrument Incubator Program to build an airborne demonstration version.

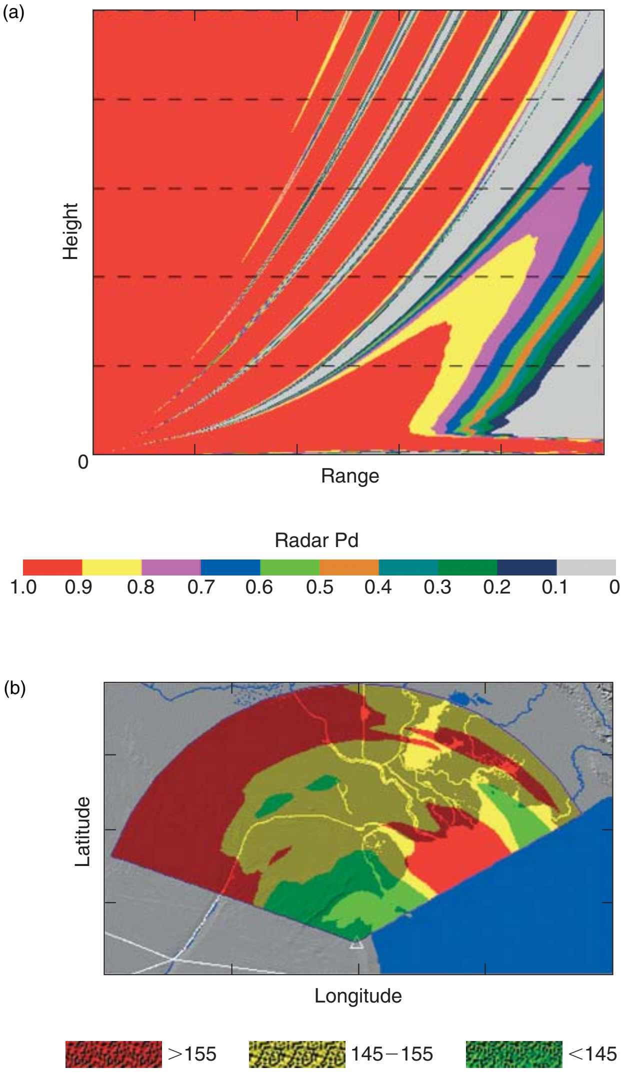

Figure 4. Operational radar propagation maps. (a) Traditional radar propagation information (vertical cuts of altitude versus range). (b) Horizontal map of radar performance. Horizontal maps are delivered to the Air Force Weather Agency in order to transition scientific research into operational systems.

Ocean Wave Models

Sea surface research and land/sea surface measurements are needed to accurately define reflective surfaces and to understand ocean and wave dynamics. As ocean surface directional wave spectra become more routinely available from *in situ* and global measurements and predictions, the need for convenient and efficient data reduction, analysis,

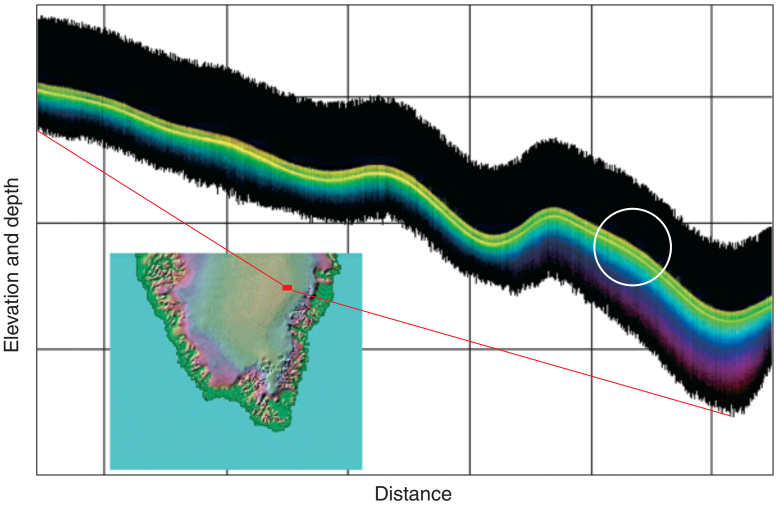

Figure 5. The APL-developed delay/Doppler radar altimeter designed to increase the accuracy of sea surface and ice covered terrain measurements. The white circle shows an area of ice–land interface. Penetration of Doppler radar signals is about 3 m of snow over glacial ice. Red lines represent the area of detailed observation.

and storage capabilities is ever-more pressing. Ocean surface wave directional spectra typically contain energy contributions from a complex mix of local winds and swells from distant storms, making them difficult to interpret. Significant wave height, peak frequency, and mean direction are often used to validate predictions, but such descriptions lose the identity of the original wind sea and swell features and can often mask serious differences between observed and predicted spectra.

To solve these problems APL developed the Wave Identification and Tracking System (WITS). WITS is a fully automated wave partitioning and swell tracking capability used to isolate, classify, and track individual wave system contributions passing by an observation point. The spectral representations of individual wave events are captured by a peak isolation routine, with wind seas identified by wave age criteria. A separate tracking algorithm identifies swell systems by source and uses gravity wave dispersion to estimate the time and location of each generation event. The results allow a systematic approach to wave validation through comparison of predicted and observed wave systems from specific wind forcing events. Furthermore, the temporal view of evolving wave systems allows quantification of time and direction offsets in the specified winds. Used to characterize the wave conditions in several past APL field tests, WITS has been licensed to an international consulting company; two additional licensing opportunities are pending.

The Laboratory is also developing an ocean wave analysis package, APL-WAVE, to enhance wave forecast capability, early high seas warnings for coastal areas and shipping lanes, wave climatology studies for coastal and offshore structures, and validation and diagnostics for global and regional wave models.

SPACE ENVIRONMENT/ SPACE WEATHER

Space is now part of our biosphere, given our permanent presence on the International Space Station as well as our ever-increasing dependence on space-based technology. Our biosphere will expand as we travel throughout space in the future, but we must be even more attentive today to natural versus anthropogenic influences on the atmosphere. For example, solar variability, eruptions, and flares have disruptive, event-based effects on space-based technology. These phenomena, typically labeled "space weather," primarily impact communications and navigation in the low-altitude ionosphere and cause radiation exposure at high latitudes. In addition, they affect electric power systems and even high-resolution miniature electronic fabrication. Space weather also produces long-term variations—ranging from years (the 11- and 22-year sunspot cycles) to centuries—in solar irradiance output as well as average flare and mass ejection rate. Solar variability may impact long-term tropospheric weather as well as our models and observations of global temperature changes.[3] (This should not, however, be interpreted to mean that solar variability is the major contributor to global warming, but its effect must be considered.)

Quest for Knowledge

TIMED

NASA's TIMED (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics) spacecraft was launched on 7 December 2001 into a polar, high-inclination orbit. Its science goals are to understand the influence of the Sun on Earth's atmosphere ranging from short time scales due to solar eruptions and flares to long time scales on the order of the solar cycle to perhaps centuries as noted above. Most of the measurements are by remote sensing and, in particular, by limb scanning to observe spectrally the profiles of atmospheric constituents. Considering these inputs can improve our understanding of the influence of human activities on long-term global change.

Figure 6 shows the results of increased electron density from TIMED/GUVI (Global Ultra-Violet Imager) ultraviolet limb scan images.[4] Enhanced density can be seen at mid-latitudes due to the magnetic storm–induced flow of electrons vertically from the equator and returning downward (and more concentrated) at mid-latitudes. The periodic signal in longitude is due to orbital scan coverage.

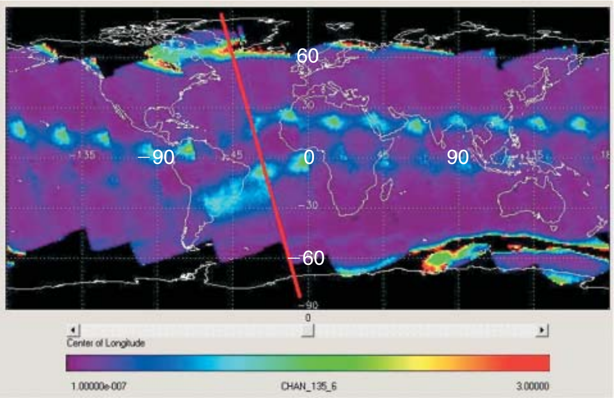

Figure 6. Nightside measurements from TIMED/GUVI ultraviolet limb scans showing oxygen ion emissions at 135.6 nm. Analysis results will include altitude profiles of atmospheric composition.

Energetic Neutral Atoms

Another means of gaining knowledge about the Earth's space environment, known as "Geospace," is a new capability to image the energetic ion population that envelopes the Earth and the Earth's radiation belts. The technique, called Energetic Neutral Atom (ENA) imaging, was invented at APL after measurement interference was found by the ISEE satellite's particle spectrometer detectors. The interference was due to energetic neutral particles produced by charge exchanged with the cold, neutral, exospheric hydrogen gas that also surrounds the Earth.[5]

APL also built the High Energy Neutral Atom (HENA) imager for two NASA missions.[6] The first two flights of these imagers are on the Saturn Cassini mission and the Geospace IMAGE mission. Figure 7, the cover of the 26 January 2001 issue of *Science*, depicts an image of ions ringing the Earth at the magnetic equator from 4 to 6 Earth radii (R_E). This population is referred to as the "ring current" because these ions circulate the equator in a clockwise fashion, creating a current that decreases the Earth's surface magnetic field. In this image, Earth's disk and dipole field lines at $L = 4$ and 8 R_E at noon (down), midnight, dawn, and dusk are sketched. The image shown is of a Geospace magnetic storm recovery phase and a nearly symmetric ring current on 9 June 2000 at 2118 UT. HENA has provided the first-ever images (2-min cadence) of geomagnetic storm ring current growth, main phase, and recovery with full particle energy resolution, finally capturing the dynamics of Earth's reaction to solar and solar wind storms.

NEAR

APL's Near Earth Asteroid Rendezvous (NEAR) mission for NASA is another research mission to understand the composition of the solar system near its origin. NEAR orbited the asteroid Eros for a year to study its composition; asteroids do not undergo the changes over time that planets experience and give an accurate record of solar system origin. Measurements of Eros' surface from the X-ray Spectrometer aboard NEAR have shown constituents that confirm original solar system composition.

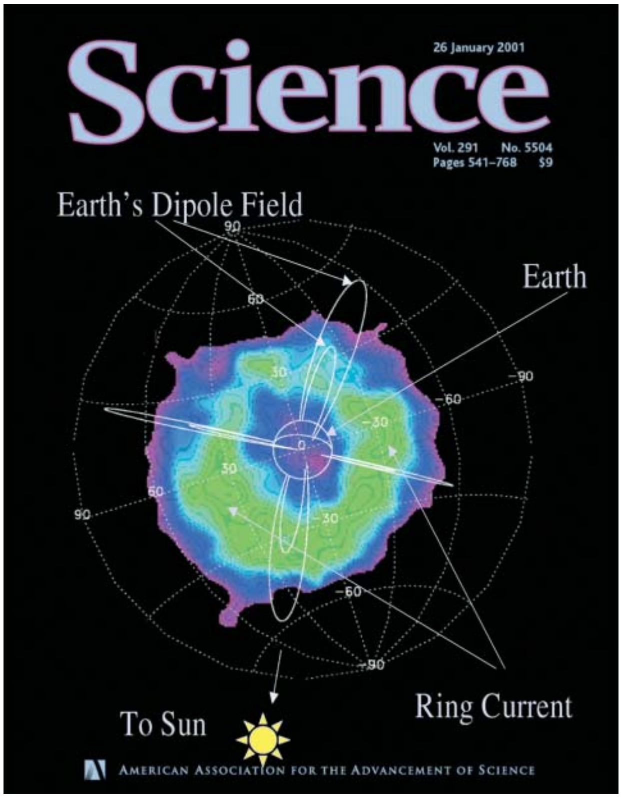

Figure 7. An image of ions ringing the Earth at the magnetic equator. (Cover from *Science* **291**(5504), 26 Jan 2001, reprinted with permission. Copyright 2001, American Association for the Advancement of Science.)

Science Applications

ACE/STEREO

Transitioning now to understanding science with a view toward applications, APL has been a pioneer in developing space weather monitoring capabilities from research platforms. Figure 8 depicts the early warning (maximum of about an hour, depending on solar wind speed) of Geospace storms based on the continuous transmission of telemetry data from the APL-built Advanced Composition Explorer (ACE). ACE monitors solar wind, density, velocity, and magnetic field, as well as energetic electrons from the Sun (at the L1 libration point). These data are received continuously via a NOAA and Air Force tracking network and distributed to both civilian and military users. The Solar Terrestrial Relations Observatory (STEREO), to be launched in 2005, will continue solar wind monitoring, but more importantly it will track coronal mass ejections from the Sun to Earth, dramatically increasing early warning capability.

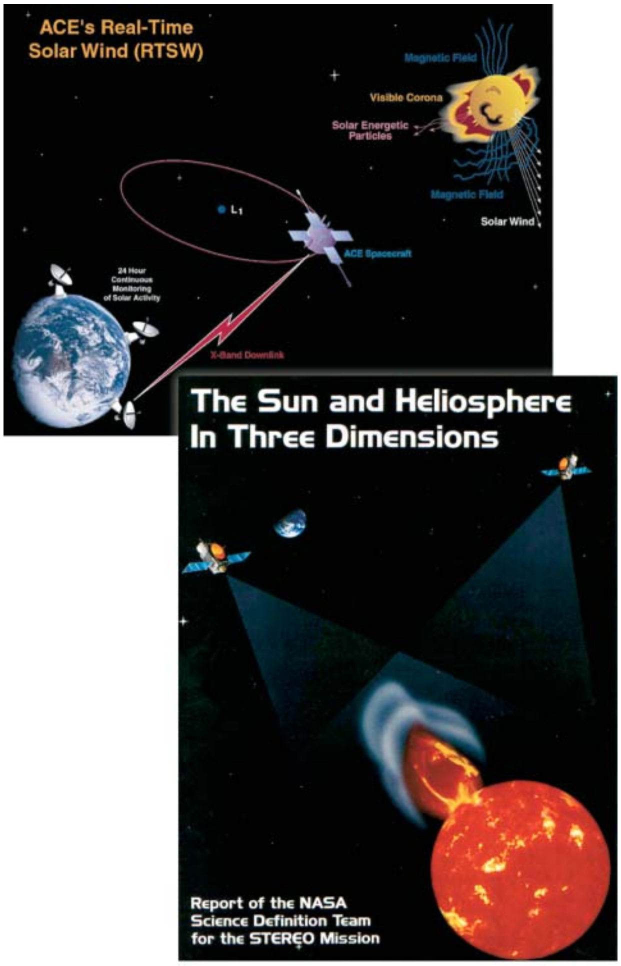

Figure 8. Artist's rendering of ACE and STEREO. Solar wind observations of impinging solar disturbances are measured *in situ* directly in front of the Earth by ACE and will continue to be imaged by STEREO as mass travels from the Sun to the Earth.

Living With a Star

The National Security Space Architect (NSSA) Office has studied a space weather architecture for protection of the nation's space assets. The office issued an architecture report in July 1999, which was subsequently approved by a joint committee and transitioned into the DoD operational platform planning process (though it involves all national space agencies). The system architecture is expected to be in place within the next few decades. NASA's Living With a Star (LWS) program is in partial response to this architecture and its requirements.

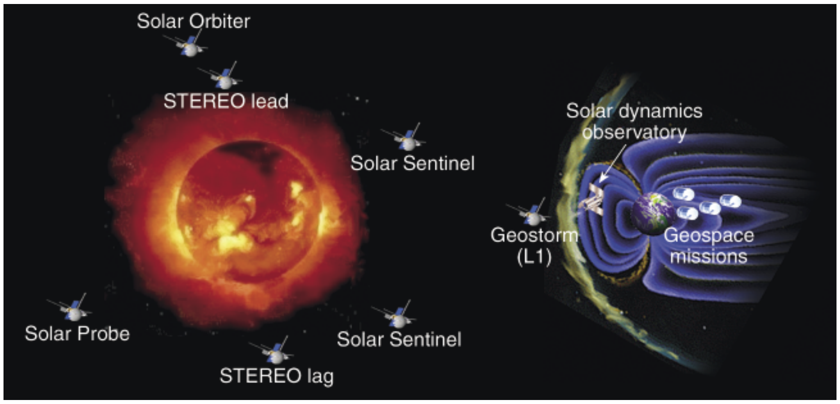

Figure 9. The NASA Living With a Star research network will be in place by the next solar maximum (2012). Its goal will be to simultaneously observe the entire Sun–Earth system and understand the dynamics of the system that lead to space weather events.

The ultimate goal is to understand the environment from the Sun to the Earth and its dynamics as a system so that disruptions can be predicted and incorporated into total system performance. By fully understanding radiation effects, space assets can be better designed to be all weather and to compensate for communication and navigation errors and outages. For example, the Tomahawk cruise missile system upgrades now being incorporated include a GPS navigation capability. This improvement gives the system a more general perspective on position and quicker updates in trajectory and tracking, but must compensate for space weather event disruptions. Models of total electron content in the ionosphere show variations in density; however, the structure (1 to 10 km) is averaged out because of modeling inadequacies and lack of observing stations. It is precisely this structure that disrupts GPS and communications signals.

Understanding the physical processes of changing electron contact in the mid-latitude ionosphere makes it possible to predict the effects of electrons on UHF and SATCOM communications as well as GPS single-frequency errors and signal outages. GPS-guided munitions can be corrected for navigation errors, and engineering systems solutions can be incorporated to compensate for problems and malfunctions. Thus many of the measurement assets recommended in the NSSA architecture are targeted toward ionospheric science and monitoring.

Figure 9 shows the planned LWS distributed network of spacecraft, which will provide continuous observations of the Sun–Earth system. This space weather research measurement system is scheduled to be in place by the next solar maximum (approximately 2012). To fully understand the dynamics of the coupled Sun–Earth system, LWS will simultaneously observe the Sun's explosive outbursts; the heliosphere's disturbance transmittal; and the Geospace solar wind–driven, inertially unstable, and internal storm processes.

An extensive Geospace network is needed because reactions to external stimuli are very complex. Geospace magnetic storm and substorm processes involve direct and somewhat linear responses to driving impulses. In addition, the massive currents (millions of amperes) that define the shape of the Earth's magnetosphere store and release energy, the dynamics of which are not understood; therefore, progress cannot be made without a global set of observations.

END-TO-END APPROACH TO SYSTEM PERFORMANCE

Operating systems for sponsor tasks must perform in consideration of environmental effects, and thus a thorough understanding of relevant effects must be incorporated into any solution if using a full systems approach. These effects must be understood scientifically and not on average or statistically. Environmental data must also be used as day-to-day input to the development of technological systems that advance our world.

Figure 10 depicts the APL Space Department's end-to-end process mentioned previously, which emphasizes the cultural APL systems approach to understanding technological systems and solving critical sponsor and national needs. Historically, APL's space mission has been to

- Scientifically understand the critical and timely questions that must be addressed to advance knowledge
- Develop commensurate mission concepts by encouraging collaboration among scientists and system engineers
- Promote concepts to interested sponsors and decision makers
- Develop, fabricate, deliver, and launch mission spacecraft and instrumentation
- Distribute science and research data to analysis teams, the science community, and the public

Using the environment as part of a system that will allow strategic and tactical advantage to our military systems is essential. For example, radar propagation paths can be dramatically affected by atmospheric inhomogeneities, refractive ducting, and terrain and land/sea interface irregularities. Performance accuracy and feedback (especially with regard to fire support) of radar propagation requires environmental input. Extensive measurements as a source of input to propagation codes are impractical, making physics-based or assimilative models essential for obtaining proper performance and accuracy measures for system designs. For example, ionospheric and atmospheric disturbances from enhanced solar activity, day-night terminator passages, terrain and ocean topography, and atmospheric boundary layers are used to predict communication outages or radar errors in defensive systems. Although similar effects will be suffered by one's own defense systems, engineering and operational solutions could be installed in order to compensate.

Likewise, as noted earlier, space weather has many adverse effects on our systems:

- Radiation damages electronics, causes predictably shortened lifetimes of spacecraft systems, and is a biological hazard.
- Satellite failures can occur with drastic consequences to technological systems. (A recent example is a high-energy X-ray flare in April 2002 that caused severe damage to the NOZOMI satellite, the first Japanese Mars Mission.)
- Extravehicular activity on the shuttle and International Space Station must be routinely scheduled around predictions of solar and geomagnetic events.
- Routine communication outages due to space storms have impacted polar airline routines and equatorial military operations.
- GPS errors and loss of signal affect precision guided munitions and location knowledge and accuracy.

In addition, space weather can adversely affect national security and threat assessment. Accurate navigational tracking of space hardware and debris is critical. For example, a July 2001 superstorm resulted in increased drag in the ionosphere, which caused orbital

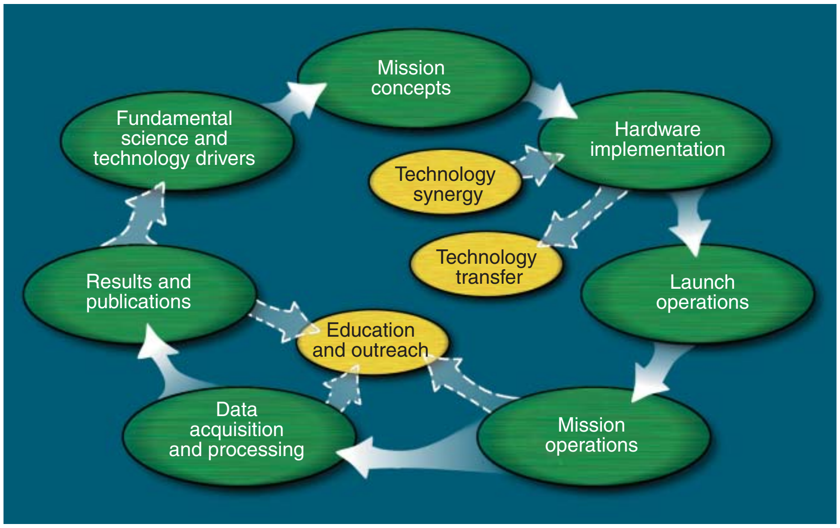

Figure 10. The APL Space Department's end-to-end capability process. The Laboratory takes a full-circle approach to national and sponsor tasks, starting with science and technology drivers through space mission stages and ending with dissemination of results.

dynamics prediction codes to fail. It was therefore not possible to track the hardware and debris.

CONCLUSION

A scientific understanding of the environment is crucial not only to advance knowledge, but also to apply that knowledge to the development of technological systems.

Radar defense systems require accurate models of performance, and performance codes must include environmental input. Environmental compensation enables systems to function robustly and allows strategic advantage. Thus an understanding of the environment is key to success within a systems approach.

By properly modeling and predicting environmental effects, we thus advance the knowledge of our habitat, history, existence, and future.

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